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Investigating foot-sock friction: A comparison of two different methodologies

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Abstract

Two different methodologies for assessing the friction between plantar skin and sock textiles are compared in this study. The first approach uses a custom-built friction plate rig. The rig consists of sock material mounted on a test plate attached to two load cells that measure normal and shear loads at the skin-sock textile interface. With this methodology, participants are required to slide their foot over the test plate whilst maintaining a targeted normal load and a relatively consistent sliding speed. The second approach uses a pneumatically-driven foot probe loading device. The device includes an instrumented probe with sock material on its contact surface. Participants are instructed to stand on a platform whilst the probe is applied to, and then driven across, the plantar aspect of foot. The cyclic motion of the probe is displacement-controlled and normal and shear loads are measured using load cells. Both approaches allow friction coefficients to be calculated from load data collected during the sliding phase of movement. Data from both approaches was examined, collected from friction tests using the same six participants and sliding contact between the first metatarsal head (1MTH) region and textiles from two commercially available running socks. Both approaches were capable of measuring the friction between 1MTH skin and sock materials and good agreement was found between them. In the dry conditions tested, the cotton-rich sock was found to provide lower friction that the anti-blister sock material.

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Keywords: Skin-sock interaction; biotribology; friction blisters; running socks

1. Introduction

Extensive in-vivo studies have been previously conducted using various methodologies to gain better understanding of the frictional interaction between human skin and surfaces. Depending on the objective of the study, researchers often carry out friction experiments using either unidirectional or reciprocating sliding interactions. In general, the measurement protocols can be divided into two main categories: a) experiments in which human subjects rub their skin against a surface [1] and b) loaded probes that are dragged against human skin [2,3]. Both approaches can offer good insights on the friction mechanisms at the skin-surface interface, and the choice of which one to use can depend on equipment availability, repeatability, accuracy, ease of use and the extent to which the real-world scenario is simulated.

In human skin studies the index finger and volar forearm are the anatomical regions that are most frequently investigated, along with many other areas such as the thighs and abdomen [2, 4]. The plantar aspect of the foot, on the other hand, has received relatively little attention despite being an area of the body that is subjected to continuous pressure and shear during walking and running [5]. The majority of previous skin friction experiments have been conducted under relatively low normal loading (≤ 20N). For walking and running, the vertical (normal) loading forces produced in the foot region can approach two to three times body weight [6] which leads to discomfort and, when combined with shear loading, the production of friction blisters [5].

This paper presents a comparison of two different methodologies used to assess foot skin-sock friction. The main purpose of conducting these studies is to compare the results from each and to consider which approach offers the best promise for continued

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work in this area. The study addresses a knowledge gap in skin friction research and contributes to the overall understanding of how foot skin interacts with sock textiles at a range of normal loads.

Nomenclature

1MTH	First metatarsal head
ABS	Anti-blister sock
CRS	Cotton-rich sock
DCOF	Dynamic coefficient of friction
SD	Standard deviation

2. Materials and methods

2.1. Study participants and test conditions

Six healthy participants (4 males and 2 females; average age in years, 28.5 ± 5.3 SD) were recruited to take part in both studies that took place at two different institutions. The first study was conducted at the University of Sheffield (Study A) whereas the second study was conducted three months later at the University of Salford (Study B). Ethical approval was obtained from the Ethics Committees at both institutions. In order to be eligible for the studies, participants were screened to not have any acute and chronic wounds or history of skin disorders (e.g. peripheral vascular disease that compromises skin integrity and neuropathy). All participants gave their informed written consent prior to testing.

The plantar aspect of the first metatarsal head (1MTH) was selected as the most appropriate test region due to the fact that this area experiences the highest in-shoe pressure [7] and shear [8] in addition to a high occurrence of blisters [9].

In both studies, the tested foot was first cleaned with water (at room temperature) to remove any contaminants and sock fibres and then dried with a paper towel and allowed to acclimatise to the room conditions for a period of 10 minutes. Skin hydration of the 1MTH area was monitored at specific intervals using the Corneometer® CM825 (Courage and Khazaka, Germany) following a standard test protocol [10] to ensure that comparable test conditions were achieved. All testing was performed in laboratory conditions with a temperature of between 20ºC to 22ºC and a relative humidity of 40 to 60%. In this study, all tests reported were carried out with the socks in a dry condition. The effects of moisture in the sock and skin-sock interface were investigated in an additional study [12].

2.2. Sock textile materials

In both studies, the same two types of commercially available running socks, were used. One is sold as “anti-blister” and the other as “cotton-rich”. Each sock had different material composition and knit patterns, as provided in Table 1. The order of testing for each sock material was randomised for each participant.

Table 1. Characteristics of the running socks used in this study.

Sock type	Material compositions	Knit pattern	Material thickness (mm)
Anti-blister “ABS”	99% nylon and 1% elastane	Simple jersey	1.18 ± 0.04 SD
Cotton-rich “CRS”	70% cotton, 29% nylon, and 1% elastane	Terry jersey	2.62 ± 0.08 SD

2.3. Data and statistical analyses

All statistical analyses were performed using SPSS 22 (Chicago, USA). The Shapiro-Wilk test was used to confirm that any data sets were normally distributed (at significance level $p > 0.05$) before Pearson’s correlation analysis was employed to determine the relationship strength between two parameters.

2.4. Study A: Friction tests using a friction plate rig

A custom-built friction plate rig, previously developed at the University of Sheffield (UoShef) [1], was first used to measure the friction between the 1MTH skin and the sock textiles. The rig includes two 50 kg-rated S-shaped load cells set up to measure the normal and friction forces. A test plate was mounted on the rig to allow a sufficiently large sock test area while allowing the transmission of the normal and shear forces.

Samples of sock were cut along the dorsal (top) line, opened out so that the inside surface was facing upwards, and stretched to approximately 50% level of strain before being secured to the test plate with double-sided adhesive tape. This level of pre-straining had been used in a previous study and found to give consistent results, whilst being relevant to real-world conditions [11]. Clamps were also applied around the material sample perimeter to further prohibit any movement between the sock and the plate, as shown in Fig. 1a. A test area of 102 mm × 54mm was marked on the plantar region of the sock to ensure that the sliding was performed on the desired region.

In order to effectively isolate the 1MTH, participants were instructed to lift their toes throughout sliding (see Fig 1a). A friction test protocol was adapted from previous studies [1, 11, 12] whereby seated participants press their IMTH region against the test plate and then push their foot forwards across the sock surface, maintaining the initial level of normal load and a relatively consistent, self-monitored, sliding velocity. This process was repeated for a range of applied normal loads.

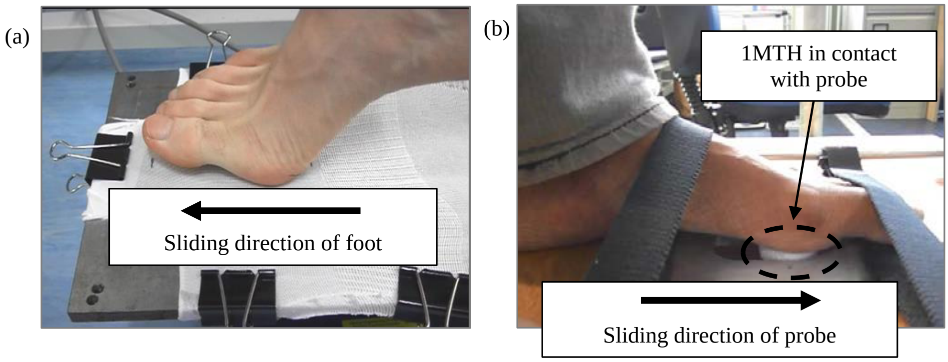

Fig. 1. Friction testing conducted using (a) the UoShef friction plate rig in Study A; (b) the UoSal foot loading device in Study B.

2.5. Study B: Friction tests using a foot loading probe device

The second study used a foot loading probe device based at the University of Salford (UoSal), originally designed to apply compression and shear forces on plantar skin without relative sliding occurring. The device includes an instrumented metal cylindrical probe of diameter 30 mm that is covered with sock material on its upper flat contact surface. Participants are instructed to remain standing on a bespoke platform, as shown in Fig. 1b, with the probe pressed against the 1MTH region of the foot. The probe is then moved downwards away from the foot and driven horizontally in the anterior-posterior direction for 250 mm. It is then driven upwards, making contact with the plantar aspect of the foot, before being driven in the posterior-anterior direction, whilst sliding across the 1MTH region, and this loading cycle is then repeated. The cyclic motion of the probe is driven using two separate pneumatic rams and is displacement controlled, through the use of two solenoid valves and a dedicated computer program. Two load cells are included in the device to measure compression (normal) and shear forces. Straps are used to aid in the position of the participant's foot and keep conditions consistent for repeated runs.

Each sock material was stretched to approximately 50% strain (as in Study A) before being securely attached to the probe using adhesive. Some trial runs were then conducted and once the participants were familiar and comfortable with the procedure, and the foot positioning was deemed correct, the foot straps were applied. Three different ram pressure settings of 0.2 mbar, 0.4 mbar and 0.6 mbar were used to generate a range of applied compression loads. For each pressure setting, the first two loading cycles were used to obtain data. Care was taken to ensure that the probe contact remained in the 1MTH skin area for each sliding part of the loading cycle.

3. Results and discussion

3.1. Generated force data from both methodologies

Figures 2a and 2b show typical examples of raw force data obtained from one participant in Study A and Study B respectively.

For Study A, normal and shear loads are plotted as a function of time to show the different phases of interaction between the 1MTH and sock textile. During phase (I) the normal (vertical) load initially increases as the foot is placed on the plate and is then maintained by the participant, before a gradually increasing shear load is applied (see Fig. 2a). In phase (II) this shear load has reached a level able to overcome the limiting friction and the foot begins to slide. In order to generate force values that relate to the dynamic coefficient of friction, a stable, central region of normal and shear (friction) force data is selected in the phase (II) region and averages are taken. This protocol has been refined in previous studies and found to give good results [1, 11, 12].

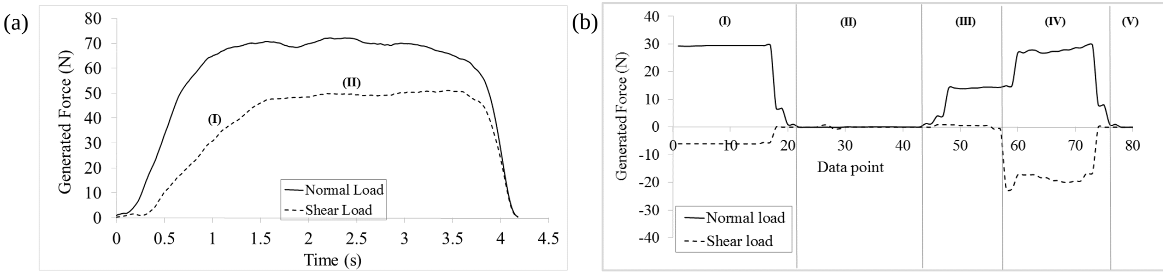

Fig. 2. Typical force data output obtained using (a) the UoShef friction plate rig in Study A; (b) the UoSal foot loading device in Study B.

In Fig. 2b the force data from Study B is shown plotted against the order of data point collected and can be divided into five different phases. Shear loads have a negative value here due to the set-up of the load cells, but it is the magnitude of the forces that is important. Phase (I) begins with the probe in its starting position, pressed against the front of the 1MTH region (as shown in Fig. 1b), before being moved away from the foot as the normal force is unloaded. Phase (II) is related to the point in the loading cycle when the probe is moved towards the back of the foot. There is no contact between foot and probe, hence no loads are measured. Phase (III) includes the initial compression loading of the probe being pressed against the plantar aspect of the foot (at the rear of the 1MTH) before being pushed horizontally by the ram, when the consequent shear loading increases rapidly. In phase (IV) the probe begins to actually move horizontally due to a relatively constant shear load and the compression loading then increases further, thought to be a consequence of the probe sliding over the bony prominence in the 1MTH region. This general effect was seen in all the participants but to different levels, dependent on anatomical variations. The probe is then unloaded and in phase (V) is made to return to its position at the rear of the 1MTH, before an entire second testing cycle is repeated (not shown in Fig. 2b). Note that the transition between phases (I) and (II), the probe unloading phase, is mirrored by this repeating action in the transition between phases (IV) and (V). In a similar protocol to Study A, central, stable regions of loading in phase (IV) are used to obtain average normal and shear (friction) force values for the sliding phase of the foot-sock interaction. These are then averaged with the measurements taken in the second testing cycle.

3.2. Comparison of methodologies

The averaged normal and sliding friction forces from both studies are shown for comparison in Figs 3a (for the anti-blister sock) and 3b (for the cotton-rich sock). Each data point results from averages taken from one test run for Study A and two test runs for Study B; standard deviation data from Study A is also provided in Table 2. Study B was capable of achieving normal (compression) loads in the approximate region of 10 to 40 N and in trial runs attempts to increase this load level, either through the ram pressure setting or the initial foot positioning, led to the risk of discomfort to participants. Although this normal load range is lower than that seen in walking and running, it is higher than the level used typically in other skin friction studies [13-15]. Study A achieved normal loads ranging between approximately 10 to 200 N, with the upper level more representative of pedestrian loading.

Both studies were able to differentiate between the participants to some degree and gave the same general trend whereby the dynamic (sliding) friction force increases with the normal force. For the anti-blister sock data (Fig. 3a), participant results were found to compare well between studies. Figure 3a (anti-blister sock tests only) contains linear fits of the participant data from Study A and it can be seen that for the majority of the participants, the data from Study B is also well described by these linear fits. The strength and significance of the linear fits are indicated by the Pearson's R^2 and p values reported in Table 2. For the anti-blister sock fits based on Study A alone, many of the datasets produced strong relationships with R^2 equal to 0.95 or above. All the datasets gave linear fits that were significant at $p < 0.05$, except participant S06 which also produced the weakest fit at $R^2 = 0.885$. Linear regression was also carried out on the participant datasets combined from both studies and the R^2 and p values for these are also reported in Table 2. Similarly high R^2 values were also found with the combined datasets, but the significance increased considerably as a consequence of the size of the datasets increasing. All gave p values of 0.001 or lower. Dynamic coefficients of friction (DCOF) were calculated for both the Study A datasets and the combined datasets, as reported in Table 2. This was achieved by interpolating the respective friction forces at 100 N normal load for each participant. For instance, participant S02's Study A data in Fig 3a produced a linear fit that indicated a sliding friction force of 59 N would be achieved at a normal load of 100 N. This results in a DCOF of 0.59, as reported in Table 2. For the anti-blister sock data, the DCOF values for each participant were very similar using either dataset (see Table 2) and both achieved similar ranking for friction by participant (for instance, participant S02 gave the highest friction values in both studies).

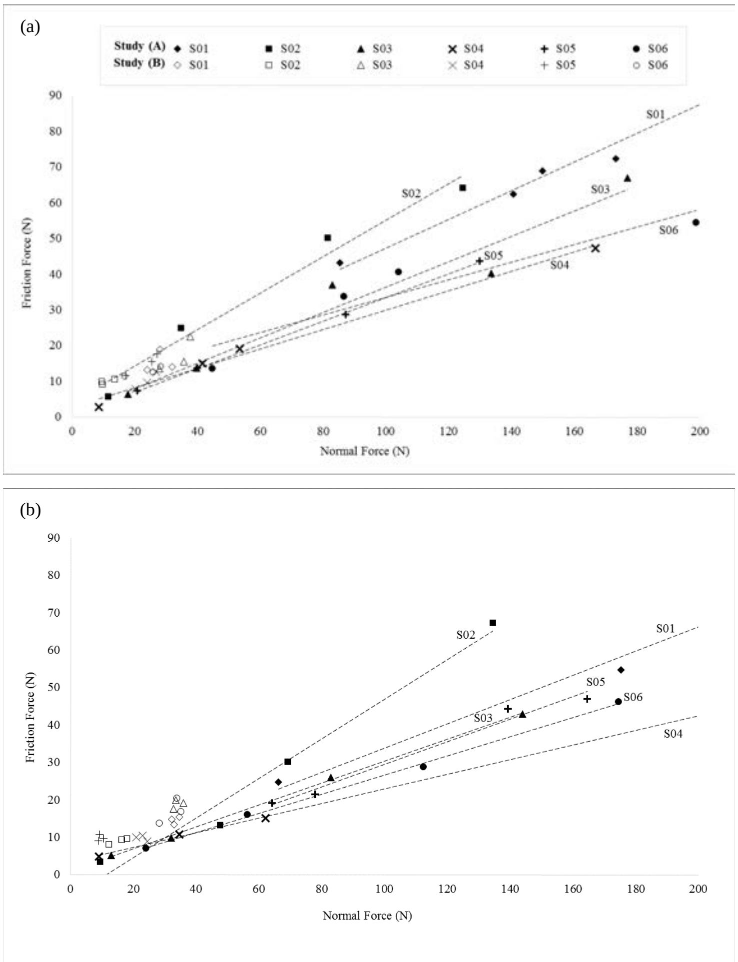

Fig. 3. Normal and friction force data for both studies with linear fits applied to Study A data for (a) the anti-blister sock; (b) the cotton-rich sock.

Table 2. Summarised statistical and DCOF data obtained from Study A and both studies combined. The level of significance is indicated by * ($p < 0.05$). NF: normal force (N); FF: friction force (N)

Sock type	Subject	Study A					Combined studies		
		R^2 value	p-value	DCOF	<NF_SD>	<FF_SD>	R^2 value	p-value	DCOF
ABS	S01	0.987	0.001*	0.45	2.15	2.54	0.993	0.000*	0.46
	S02	0.970	0.015*	0.59	2.08	1.77	0.981	0.000*	0.55
	S03	0.947	0.005*	0.37	1.48	1.97	0.938	0.000*	0.37
	S04	0.990	0.005*	0.33	2.27	2.41	0.987	0.000*	0.30
	S05	1.000	0.000*	0.34	0.63	1.43	0.938	0.000*	0.34
	S06	0.885	0.059	0.34	1.06	1.29	0.941	0.000*	0.33
CRS	S01	0.990	0.005*	0.34	3.75	2.96	0.995	0.000*	0.35
	S02	0.975	0.013*	0.39	0.64	1.71	0.962	0.000*	0.47
	S03	0.999	0.000*	0.33	0.23	0.67	0.899	0.001*	0.32
	S04	0.999	0.000*	0.33	0.95	2.75	0.992	0.000*	0.23
	S05	0.978	0.137*	0.29	1.73	1.69	0.972	0.000*	0.31
	S06	0.998	0.001*	0.27	0.40	0.91	0.912	0.001*	0.28

Analysis of the data from the cotton-rich sock tests in Fig. 3b shows less close friction behaviour between the two studies, but DCOF values from the Study A dataset and combined dataset gave good comparison for all of the participants except S02 and S04. In terms of sock frictional performance, the cotton-rich sock was consistently found to produce lower friction than the anti-blister sock for each set of participant data (in the dry conditions tested). This finding was confirmed in an additional study that included more participants, as well as investigating moisture effects [12].

In general, both approaches gave similar results in terms of the trends observed and the participant and textile-specific friction values produced. This was despite the fact that the level of loading differed between the methodologies as well the interaction between foot and sock; Study A used one area of the foot sliding across the sock surface, whereas Study B used one area of sock sliding across the foot surface. This has given confidence that both approaches have validity in further studies of skin-textile frictional interactions. The approach used in Study B is recommended for situations where it is difficult for participants to control the loading in a consistent manner and/or in a particular location. However, the approach used in Study A (with the current set-up) allows greater loading to be applied, that is more representative of pedestrian interactions, and therefore more likelihood that statistical differences can be found between data sets using different input parameters. Further work using this approach has extended the number of participants and included the effects of moisture in the contact, as well as linking findings with other measured sock properties, in order to predict frictional behaviour in real-world scenarios [12, 16].

4. Conclusions

This study has compared two different methodologies to measure foot skin-textile friction; the first using a friction plate rig and the second using a foot loading probe. Both approaches were capable of measuring the friction between 1MTH skin and sock materials and good agreement was found between them, particularly with measurements from the anti-blister socks. In the dry conditions tested, the cotton-rich sock was found to provide lower friction that the anti-blister sock material. The first testing approach has been selected for use in further skin-sock friction experiments due to its capability of achieving higher loading conditions.

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